

Optimal carbon dioxide application for organ protection in cardiac surgery

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Background: Cardiac surgery is associated with an important risk of central or peripheral organ damage, attributed in part to air embolism from incompletely deaired cardiac chambers. Insufflation of carbon dioxide into the thoracic cavity is widely used for organ protection in cardiac surgery.

Methods: In patients operated on through a sternotomy, the gas was insufflated through a standard cardioplegia line (group I, $n = 10$) or a Jackson-Pratt drain (group II, $n = 10$), with flow rates of 2, 4, and 6 L/min. In patients undergoing mitral valve surgery through a right anterolateral minithoracotomy, application through a gas port (group III, $n = 10$) was compared with application through a Veress needle (group IV, $n = 10$). In groups I and IV measurements were repeated with a gauze sponge to divert the gas stream.

Results: At a flow of 2 L/min, carbon dioxide levels in the thoracic cavity reached $52\% \pm 30\%$ in group I and increased to $81\% \pm 27\%$ when a gauze sponge was used. In group II a level of $91\% \pm 5\%$ was achieved. In minimally invasive procedures carbon dioxide levels reached $92\% \pm 6\%$ in group III and $60\% \pm 25\%$ in group IV without a gauze sponge and $97\% \pm 2\%$ in group IV with a gauze sponge. Increasing flow rates from 2 to 6 L/min decreased carbon dioxide levels in the thoracic cavity. Arterial blood gas analysis did not reveal critical levels of partial pressure of carbon dioxide at any time.

Conclusions: For optimized carbon dioxide concentrations during cardiac procedures, jet effects in the thoracic cavity have to be avoided. The highest levels were achieved with infusion lines covered by a gauze sponge or a perforated drain for conventional operations and a sponge-covered Veress needle or a gas port for minimally invasive approaches.

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Insufflation of carbon dioxide (CO₂) to the operative field to prevent cerebral or myocardial damage by means of air embolism has been reported since 1957 in cardiac surgery.¹ With the advent of minimally invasive valve surgery, deairing of cardiac chambers has become more difficult, and replacing air in the operative field with a more soluble gas has become a widely used technique. In recent studies neurocognitive impairment has been observed in up to 88% of patients after cardiopulmonary bypass (CPB) procedures, and disturbances might be progressive and persistent.² Introduction of air into the CPB circuit, resulting in cerebral microembolization, might contribute to postoperative cognitive impairment.³ Despite carefully performed deairing procedures, transcranial Doppler studies revealed a large amount of emboli during the first ejections of the beating heart.⁴ Air emboli always remain in the arterial circulation until complete absorption, and they only occasionally dislodge and flow downstream.⁵ CO₂ fills the thoracic cavity by means of gravity and replaces air if

TABLE 1. Preoperative and intraoperative data

	Group I (n = 10)	Group II (n = 10)	Group III (n = 10)	Group IV (n = 10)
Sex	7 males	8 males	3 males	7 males
Age (y)	61 ± 22	60 ± 16	49 ± 25	50 ± 14
Size (cm)	170 ± 11	177 ± 10	165 ± 10	178 ± 7
Weight (kg)	76 ± 13	84 ± 22	66 ± 13	74 ± 10
CPB flow (L/min)	4.4 ± 0.3	4.8 ± 0.6	4.2 ± 0.5	4.6 ± 0.3
CPB (min)	124 ± 32	156 ± 40	134 ± 18	171 ± 34
Crossclamp time (min)	78 ± 31	101 ± 36	83 ± 13	104 ± 22

adequately insufflated. Because solubility of CO₂ is better than that of air, occlusion or flow disruption in arteries of the brain or the heart is thought to be diminished. In 1940, Moore and Braselton⁶ showed that the lethal dose of air was 12 times less than that of CO₂ injected into the pulmonary vein. In our institution all patients undergoing cardiac surgery through limited incisions are operated on with CO₂ insufflation as a matter of policy.

An indirect method to determine the effectiveness of CO₂ application to the operative field by measurement of oxygen concentration was presented by Selman and colleagues¹ in 1967. The aim of our study was to evaluate different application methods with regard to optimized gas flow by using direct measurements of CO₂ in the thoracic cavity. Measurements were performed in standard procedures through a median sternotomy and in minimally invasive approaches through limited incisions. Because complications caused by systemic resorption of CO₂ and an increase of arterial Pco₂ with acidosis have been described, blood gas analyses were evaluated frequently in our patients.

Patients and Methods

In patients of groups I and II, operations were performed through a complete median sternotomy. Procedures in group I were aortic valve replacement (n = 4) combined with mitral valve replacement (n = 1) or with coronary artery bypass grafting (n = 2), mitral valve repair (n = 2), and atrial septal defect closure (n = 1). Procedures in group II were aortic valve replacement (n = 2) combined with coronary artery bypass grafting (n = 1), aortic valve replacement with a conduit (n = 2), aortic valve reconstruction (n = 1) combined with replacement of the ascending aorta (n = 1), and mitral valve reconstruction (n = 3). Preoperative and intraoperative data are summarized in Table 1.

After systemic anticoagulation (300 IU/kg Liquemin, Roche), cannulation of the ascending aorta was performed with a standard cannula (Jostra AG). For cannulation of the right atrium, we used a 2-stage cannula or bicaval cannulation for mitral valve procedures, respectively. CPB was instituted with a Quadrox (Jostra AG) capillary membrane oxygenator. The circuit was primed with 1500 mL of Ringer's lactate solution, 500 mL of 6% hydroxyethyl starch, 100 mL of 20% mannitol, and 150 IU/kg heparin. CPB was conducted with a flow of 2.4 L/min per square meter of body surface area, rectal temperature was lowered to 30°C ± 2°C, and

alpha-stat management was applied. Antegrade and retrograde cold blood cardioplegia were administered in an intermittent fashion. The arresting dose was 1000 mL, and a maintenance dose of 400 mL was infused every 20 minutes. Anesthesia was maintained with sufentanyl, pancuronium, or propofol, and ventilation was performed with an O₂/N₂O mixture establishing an inspired oxygen fraction (Fio₂) of 0.5 and aiming at a Pco₂ of 35 to 40 mm Hg before and after CPB. We used intermittent cardiomy suction and continuous venting through the apex of the left ventricle or the left atrium in mitral valve procedures, respectively.

CO₂ was applied by using a perfusion line (2-mm inner diameter) sutured to the left side of the pericardium in group I. After consecutive measurements at flows of 2, 4, and 6 L/min, the perfusion line was covered with a gauze sponge to divert the gas stream, and measurements were repeated. Ten minutes after stable levels of CO₂ in the operative field had been reached, arterial blood gas analyses were performed. Gas flow through the oxygenator and oxygen concentration (Fio₂) were adjusted by the perfusionist, according to blood gas checks and expectation of Pco₂ changes during gas application. In group II CO₂ was applied with a commercially available perforated drain (Jackson-Pratt, Allegiance) placed in the pericardial sac left and posterior to the heart. Deairing of cardiac chambers was performed before release of the aortic crossclamp through the apex of the left ventricle, the ascending aorta, and the left atrium in mitral valve procedures. The procedure was repeated on the beating heart. Venting through the ascending aorta was continued until the heart ejected and extracorporeal circuit was reduced.

Patients in group III and IV were operated on through right anterolateral thoracotomies through a 7-cm skin incision. In group III 7 patients underwent mitral valve repair, and 3 patients underwent mitral valve replacement. In group IV 9 repairs and 1 replacement were performed on the mitral valve. For patients' preoperative and intraoperative data, see Table 1. CPB was instituted after cannulation of the femoral artery and vein (with cannulas fabricated by Jostra AG). Cold blood cardioplegic solution was applied through a needle in the ascending aorta. A transthoracic clamp was used for aortic crossclamping (Scanlan Inc). The management of CPB and anesthesia was not different from that in our patients operated on through a median sternotomy, except for selective single-lung intubation to allow deflation of the right lung. CO₂ was insufflated beginning with the start of CPB until the atrium was closed. In group III a separate gas port with a 5-mm inner diameter (Endopath, Ethicon) was used. In group IV measurements were performed after introduction of a Veress needle with a 2-mm inner diameter. Afterward, the needle was covered

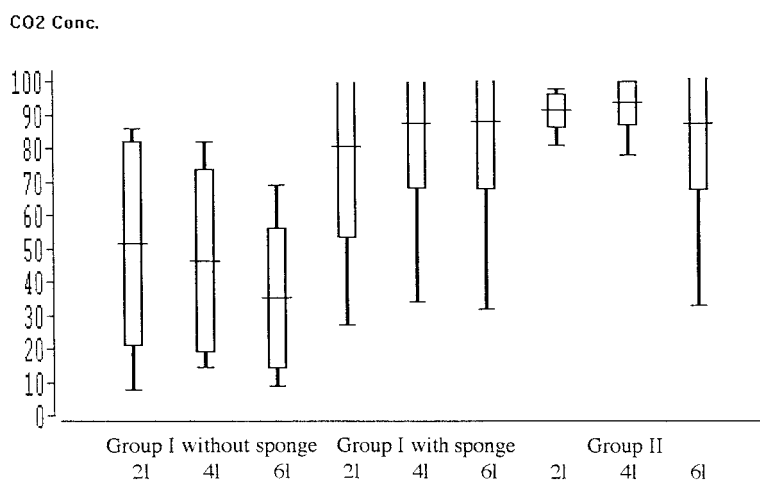


Figure 1. CO₂ concentrations measured at the level of the left ventricular cavity, with operations performed through median sternotomy. Demonstrated are mean, SD (box plots), and range of values (T bars).

with a gauze sponge, and measurements were repeated with gas flow of 2, 4 and 6 L/min. Blood gas analyses were performed as described above. For deairing of the cardiac chambers, a vent in the left atrium and another in the aortic root was used, and the ascending aorta was punctured with a needle.

We used an infrared CO₂ analyzer (BUSE), allowing for measurements of CO₂ concentration in the operative field, at the level of the left ventricular cavity. The analyzer aspirates gas samples through a plastic tube. Results are indicated with a time delay of a few seconds and a sensitivity of 0.5%. For blood gas analyses, ABL System 625 (Radiometer Medical) was used.

The study was approved by our institutional ethics committee. For statistical analysis, the SAS software package was used (SAS, Inc). The Duncan multiple range test was applied to test for significance between the different methods of application and results of blood gas analyses. Data are presented as mean and SD of the mean.

Results

CO₂ concentrations in the thoracic cavity are depicted for operations performed through a median sternotomy in Figure 1 and in Figure 2 for minimally invasive procedures. At 2-L/min flow, CO₂ levels in the thoracic cavity reached 52% \pm 30% in group I and increased to 81% \pm 27% when a gauze sponge was used ($P < .001$). In group II a level of 91% \pm 5% was achieved, which was significantly elevated compared with that in uncovered cardioplegia lines of group I ($P < .001$) and slightly higher than that with sponge-covered lines (not significant). Additional measurements with 10-L/min flow were performed according to the literature.⁷ No increase of CO₂ concentrations compared with lower flow rates could be shown (90% \pm 7% vs 91% \pm 5% with 2 L, not significant). In minimally invasive procedures CO₂ levels reached 92% \pm 6% in group III and 60% \pm 25% in group IV without a gauze sponge and 97% \pm 2% in

group IV with a gauze sponge. The highest CO₂ concentrations were achieved with sponge-covered Veress needles and gas port insufflation, respectively ($P < .001$ vs uncovered Veress needles).

Results of blood gas analyses are shown in Table 2. For groups I and IV, values are presented for the higher operative field concentrations achieved with gauze sponges. Because significant field levels of CO₂ have already been achieved with a flow of 2 L/min, the measurements with 6 L/min were taken after approximately 30 minutes of exposure to a CO₂ atmosphere. Our perfusionists increased gas flow through the oxygenator to avoid systemic accumulation of CO₂. This was significant in minimally invasive procedures of group IV, in which gas flow was increased from 2.8 \pm 0.5 to 3.6 \pm 0.6 L/min ($P = .0049$). As a result of a slight overcorrection, Pco₂ levels in serial blood gas analyses decreased from 42.3 \pm 6.1 mm Hg with 2-L/min insufflation to 36.9 \pm 6.7 mm Hg with 6-L/min CO₂ insufflation (not significant). However, systemic Pco₂ remained within normal ranges in all groups (Table 2). Fio₂ was significantly reduced by the pump technicians in group IV, from 0.45 \pm 0.07 to 0.39 \pm 0.05 ($P = .007$), resulting in lower arterial Po₂ values (251 \pm 29 mm Hg with 2-L/min and 158 \pm 45 mm Hg with 6-L/min gas insufflation, $P = .016$). All blood gas analyses remained within normal ranges, despite varieties of CO₂ field concentration and adaptations of oxygenator gas flow and oxygen concentration.

There was no perioperative mortality in the study groups. One patient in group I was reoperated on for bleeding and recovered with prolonged confusion. One patient in group II presented with low cardiac output syndrome after double valve replacement and underwent respirator therapy for 6 days after the operation.

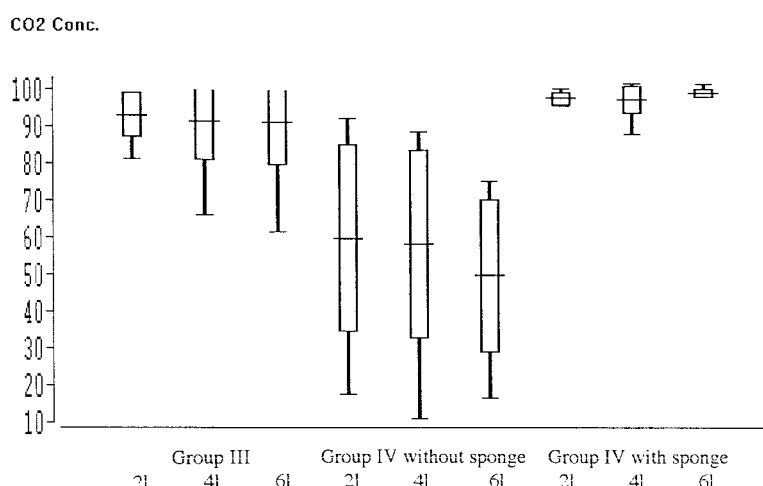


Figure 2. CO₂ concentrations measured at the level of the left ventricular cavity, with minimally invasive procedures. Demonstrated are mean, SD (box plots), and range of values (T bars).

TABLE 2. Blood gas analyses

	CO ₂ insufflation (L)	CO ₂ concentration (%)	Pco ₂ (mm Hg)	Po ₂ (mm Hg)	Temperature (°C)	Fio ₂	Gas flow
Group I (sponge)	2	80.5 ± 27	38.4 ± 4	210.4 ± 59	30.8 ± 2.4	0.47 ± 0.08	2.6 ± 1.0
	4	87.6 ± 19	40.6 ± 10	195.9 ± 80	31.4 ± 2.4	0.48 ± 0.08	2.7 ± 1.3
	6	88.2 ± 20	41.6 ± 8	201.8 ± 79	32.0 ± 2.8	0.45 ± 0.12	3.3 ± 1.9
Group II	2	91.4 ± 5	40.6 ± 8	199.3 ± 47	29.6 ± 2.8	0.41 ± 0.09	3.3 ± 1.1
	4	93.7 ± 6	39.5 ± 8	176.6 ± 38	30.1 ± 2.7	0.40 ± 0.09	3.6 ± 1.4
	6	87.8 ± 20	39.8 ± 10	185.4 ± 72	31.0 ± 2.7	0.40 ± 0.09	3.5 ± 1.6
	10	90.3 ± 7	42.4 ± 11	165.0 ± 60	29.6 ± 4.1	0.38 ± 0.11	4.0 ± 1.7
Group III	2	92.3 ± 6	39.9 ± 6	174.9 ± 71	29.9 ± 1.5	0.39 ± 0.07	3.0 ± 1.0
	4	90.8 ± 11	39.5 ± 6	177.7 ± 65	30.2 ± 1.7	0.38 ± 0.07	3.4 ± 1.0
	6	90.4 ± 12	36.6 ± 5	152.7 ± 73	30.7 ± 2.2	0.40 ± 0.08	4.1 ± 1.3
Group IV (sponge)	2	97.5 ± 2	42.3 ± 6	251.2 ± 29	29.5 ± 1.4	0.45 ± 0.07	2.8 ± 0.5
	4	97.2 ± 4	38.8 ± 5	197.3 ± 40	29.2 ± 0.9	0.38 ± 0.06	3.5 ± 0.6
	6	98.9 ± 1	36.9 ± 7	157.9 ± 45	30.1 ± 2.6	0.39 ± 0.05	3.6 ± 0.6

Discussion

CO₂ is used to replace air in the operative field during cardiac procedures with the assumption that the more soluble CO₂ will reduce the amount and sequelae of gaseous emboli. CO₂ might be resorbed already in the cardiac chambers, and therefore the amount of gas bubbles in the ascending aorta can be reduced, as shown in an echocardiographic study.⁷ In addition, embolic bubbles obstructing a peripheral vessel might be resorbed quicker when they consist of a high concentration of CO₂. For the latter, however, we found no scientific proof in the literature. It is obvious that only a significant increase in the CO₂ concentration in the cardiac chambers can influence resorption rates of residual gas and by this can influence clinical outcome.

There are several methods of CO₂ application described in the literature. Many surgeons use standard perfusion lines with 2- to 3-mm inner diameter with a flow of 2 to 10 L/min

CO₂ to replace air in the thoracic cavity and cardiac chambers. This is done under the assumption that the heavy CO₂ will fill the operative field by means of gravity. Shang and Rosen⁸ showed that a flow of greater than 5 L/min did not increase effectiveness of air replacement in the thoracic cavity. Webb and colleagues⁷ used a perforated drain (Jackson-Pratt) and a flow of 10 L/min CO₂, and they demonstrated a reduction of gas bubbles in the cardiac chambers visualized by means of transesophageal echocardiography. Their group did not measure CO₂ concentrations in the operative field directly but concluded from oxygen concentrations that they reached CO₂ concentrations of 93% and greater. Our results indicate that concentrations of greater than 90% are achieved if only 2 L/min is applied. Selman and coworkers¹ showed that greater than 90% of air can be displaced from the operative field if a CO₂ disperser is used. Increasing flow rates lead to reduced concentrations of CO₂

in the thoracic cavity if ¼-inch tubing was used for gas application. Even if a knitted blood vessel prosthesis was used as a disperser, CO₂ levels decreased if more than 7 L/min CO₂ were applied.

These results are confirmed by our direct measurements in the thoracic cavity. We showed that application is effective if a commercially available perforated drain (Jackson-Pratt) or a simple cardioplegia line covered with a gauze sponge is used in cardiac procedures. Our results in minimally invasive procedures indicate that insufflation through a gas port or dividing the gas stream of an endoscopic needle with a gauze sponge increases CO₂ concentration in the operative field. Uncovered lines or endoscopic needles showed significantly lower CO₂ concentrations. Most probably, high gas jets flushed the operative field, and the generated gas stream dragged air into the pericardial sac. Flooding of the operative field by means of gravity does not occur with these gas jets. Even with diverted gas jets, concentrations tended to decrease at higher flow rates.

Several authors described an increase of CO₂ in blood with acidosis when CO₂ was insufflated into the thoracic cavity.⁹⁻¹² This is in part dependent on the use of cardiotomy suction or venting. There were methods described to monitor CO₂ levels in the cardiotomy reservoir and to prevent accumulation of CO₂ by flushing excessive CO₂ with oxygen in the oxygenator.¹² In our patients the Pco₂ in arterial blood samples did not reach critical levels, although conventional cardiotomy suction and venting was used, and CO₂ was applied from the start of extracorporeal circulation until release of the aortic crossclamp. Because of lack of experience and reliable data with pump management under these conditions, our perfusionists corrected the gas flow according to their expectations and results of blood gas analyses. However, this led to significant but clinically irrelevant overcorrection in group IV. With increasing gas flows, the oxygen concentration provided (Fio₂) was reduced, and consecutively, Po₂ levels in arterial blood samples declined to more physiologic levels.

Concentrations of greater than 90% of CO₂ in the oper-

ative field are possible with our means of application to achieve effective reduction of gaseous cerebral and coronary artery emboli in cardiac surgery. A gas flow of 2 L/min is sufficient, as long as gas jets are diverted. Gas concentrations did not increase with flow, most probably because higher exit velocity causes jets, flushing the thoracic cavity with room air. Systemic accumulation of CO₂ with severe acidosis was not observed. However, extracorporeal circulation management had to be adapted.

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